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SPECIAL TOPIC

REVIEW

# On the timing and duration of the destruction of the North China Craton

XU YiGang[1†], LI HongYan[1,2], PANG ChongJin[1,2] & HE Bin[1]

[1] Key Laboratory of Isotope Geochronology and Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China;
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

**The timing and duration of the destruction of the North China Craton, which is pivotal to understanding the destruction mechanism and its geodynamic controlling factors, still remain controversial. On the basis of the principles of magma genesis and evolution, first we outline magmatic expressions that can be related to cratonic destruction, then use magmatic and basin evolution trends to constrain the timescale of the lithospheric thinning in North China. The main conclusions include: (1) the thinning of the lithosphere beneath the North China Craton might have started, at least locally, since late Carboniferous-late Triassic, attained its climax during the late Jurassic-early Cretaceous, and continued till the end of late Cretaceous-early Cenozoic. The destruction of the North China Craton was a relatively slow, rather than a dramatic process. (2) The weakened lithospheric zones along the margins and interiors of the craton played an important role in cratonic destruction, partly accounting for the heterogeneous pattern of cratonic destruction. (3) The tectonic factors that controlled the destruction of the North China Craton may be multiple. The late Carboniferous southward subduction of the Paleo-Asian plate and the late Triassic collision between North China and South China may have re-activated the craton by influencing the thermal and integral structure of the craton. The Pacific subduction underneath the eastern Asian continent played a determinant role in the cratonic destruction, governing the distribution patterns of post-Mesozoic basins and major tectonic configuration, temporal change of magmatism and formation of the North-South gravity lineament.**

magmatism, basin analysis, cratonic destruction, timing and duration, North China

GEOCHEMISTRY

As the central part of investigations into the evolution of the North China Craton, the assessment of the timing and duration of the lithospheric thinning is vital to understanding the destruction mechanism and its geodynamic controlling factors. Determining the timing and duration of the cratonic destruction requires a comprehensive analysis of magmatism, tectonic evolution and paleogeography. Given the fact that there are controversies over the geologic expression of cratonic destruction, the current knowledge about the timing and duration of the cratonic destruction mainly stemmed from studies on magmatism. It is worth noting that different researchers arrive at completely different conclusions although they all studied magmatism. For instance, on the basis of high Ni and Cr contents, Gao et al.[1] proposed that the Jurassic high-Mg adakitic rocks from western Liaoning were derived by partial melting of delaminated crust, which subsequently interacted with the upper mantle. This petrogenetic model implies that the destruction of the North China Craton took place in the middle Jurassic. Accumulating data reveal two major episodes of large scale magmatism in North China: 190—155 Ma and 135—115 Ma[2,3]. Wu et al.[4] related the Jurassic magmas to the Pacific subduction underneath the Asian con-

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†Corresponding author (email: yigangxu@gig.ac.cn)
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tinent, and they suggested that only early Cretaceous (135—115 Ma) magmatism resulted from lithospheric thinning and cratonic destruction. In other words, the destruction of the North China Craton accomplished over a very short period. Jiang et al.[5] identified late Jurassic lamproites in eastern Liaoning and inferred that the onset of the cratonic destruction was late Jurassic. Xu et al.[6,7] stressed that the destruction of the North China Craton was not a short process. At the beginning of cratonic destruction, the magmatism was characterized by consumption of enriched mantle components. Because the lithosphere was relatively thick at that time (⩾100 km), the consumption of fusible components during previous stages resulted in a relatively dry lithospheric mantle which is hard to melt further, generating a magmatic hiatus. The asthenosphere arises at the shallowest level, when the lithosphere was thinnest. Under such a circumstance, large degree of partial melting of the asthenosphere took place, generating tholeiites. On the basis of Mesozoic-Cenozoic magmatic evolution, Xu et al.[6–11] suggested a prolonged (>100 Ma) lithospheric thinning process. Lu et al.[12] considered the late Cretaceous-Cenozoic asthenosphere-derived basalts in North China are the direct expression of lithospheric thinning. Consequently, they suggested the climax of lithospheric thinning must be after 65 Ma. The extent of lithospheric thinning in Mesozoic was insignificant.

Why do these controversial occur? How to reconcile the relationship between magmatism and cratonic destruction is a must-do-task in the present investigation into the North China cratonic evolution. In addition, other geologic expressions related to cratonic destruction should be taken into account in this study. On the basis of the principles of magma genesis and evolution, this paper first outlines magmatic expressions that are related to cratonic destruction, then use magmatic and basin evolution patterns to constrain the timescale of the lithospheric thinning in North China.

## 1 Magmatism related to cratonic destruction

### 1.1 Mafic magmas

The destruction of a craton implies a considerable thinning of the lithosphere. Associated with lithospheric thinning is upwelling of the convective asthenosphere and modification of the thermal structure of the lithosphere. As a result, the involvement of mantle components in magmatism can be considered as one of type expressions of cratonic destruction. Mafic magmas are generated by partial melting of the upper mantle. Their formation and composition are controlled by several factors including source characteristics, degree of partial melting, mantle potential temperature and lithospheric thickness. Distinction of the relative importance of these factors in magma generation is the key to constraining mantle evolution and cratonic destruction using composition of mafic rocks.

The pre-request of mantle melting is the cross over between geotherm and mantle solidus. The addition of volatiles (such as $H_2O$ and $CO_2$), increasing mantle temperature and adiabatic ascent of the asthenosphere subsequent to lithospheric extension can induce partial melting of the mantle. In reality, mantle melting may proceed via some combined mechanisms. For example, the generation of some continental potassic magmas may be jointly caused by volatile addition and local thermal perturbation; formation of an igneous province may involve a number of melting mechanisms, and even change-over of mechanism with time.

Magmatic expression of cratonic destruction (or lithospheric thinning) includes:

(1) Cratonic magmatism. Magmatism is relatively rare in cratons, but the types of igneous rocks that do occur are instructive as to melt compositions and the melting conditions of cratonic lithosphere. In general, kimberlites occur in the central parts of cratons, whereas ultramafic lamprophyres and other carbonate-rich alkaline rocks become more important towards the periphery of cratons[13]. The formation of kimberlites is likely related to mantle plumes. The melts generated by initial melting of mantle plumes cannot erupt to the surface, instead they impregnate lower cratonic lithosphere resulting in the formation of volatile-bearing metasomatic assemblages. During the later stages of thermal perturbation, these highly metasomatized mantle domains become the source of ultramafic lamprophres[13]. The occasional occurrence of diamonds in these rocks proves that their origin must be at depths greater than 160 km, attesting that ultramafic magmas can be considered as magmatic expression of early stage of cratonic destruction. In some cases, rifting of cratons can lead to the formation of a new oceanic crust, with the Labrador Sea as a type example. Before the final opening of the Labrador Sea, nephelinites and melilitites were erupted for which experimental melting studies place their origin at

90－100 km. Because the age difference between nephelinites/melilitites and lamprophyres is 400 Ma in the Labrador Sea, Tappe et al.[14] suggested a removal of a minimum of 60 km of the cratonic lithosphere in the intervening 400 Ma.

(2) Transition from enriched to depleted mantle source. It is generally accepted that the continental lithospheric mantle cannot act as the source of magmas due to its refractoriness and its “cold” thermal state[15]. It has been demonstrated by theoretical and thermal modeling that, under the circumstance that the lithosphere and asthenosphere share similar melting behavior, over 95% melting takes place in the asthenosphere, whereas the possibility that the lithosphere melts to generate magmas is very low[16]. Nevertheless, the presence of hydrous minerals in mantle xenoliths suggests that the lithospheric mantle is locally wet[17]. The presence of water can considerably lower the temperature of the mantle solidus (by 400－500℃)[18]. Hence, the enriched lithospheric mantle can be the source of intraplate basalts[19].

When thermal gradient increases during lithospheric thinning, the source of magmas can shift from the lithosphere (enriched mantle) to the asthenosphere (depleted mantle). Because enriched components in the continental lithosphere (especially those with high Sr and low Nd isotopic ratios) cannot be replenished immediately, the consumption of these fusible components in the early stage will confine late stage magmas within the asthenosphere. In this sense, the transition from enriched mantle to depleted mantle source is irreversible. So such a change in magma source can be considered as an indicator of lithospheric thinning[11].

(3) Asthenosphere-derived magmas. The asthenosphere cannot melt until the thickness of the lithosphere is less than 65－80 km[15]. Such a phenomenon mainly occurs in rift-extended regions or in areas affected by mantle plumes[20]. In this sense, the appearance of asthenosphere-derived magmas is indicative of a thin lithosphere. Nevertheless, asthenospheric magmas can equally be produced during lithospheric accretion/thickening. Therefore, for a given period, asthenosphere-derived magmas are not necessarily related to lithospheric thinning. The temporal variation in magmatic composition is more appropriate to back-up the lithospheric history.

(4) Shift from asthenosphere-derived tholeiite to alkali basalts. The melting behavior of the asthenospheric mantle can be described using a melting column model[21]. Given the large-scale compositional homogeneity of the convective asthenosphere, the composition of asthenosphere-derived basalts therefore depends on two main factors, including mantle temperature and lithospheric thickness at a given region[15,21]. These two parameters govern the initial depth and final depth of mantle melting. The initial melting depth is temperature dependent, the higher the temperature is, the greater the initial melting depth is. The final depth of melting is controlled by the lithospheric thickness. The upwelling of the asthenosphere is hampered by the rigid lithospheric lid. Consequently, melting depth under a thick lithosphere is greater than that under a thin lithosphere[11]. This is the so-called lithospheric lid effect. Experimental study shows that small degrees of partial melting at high pressure (> 3.0 GPa) produces magmas with more normative nepheline (alkali basalts), while large degree of melting at lower pressure (1.5－2.5 GPa) produce magmas with normative hypersthene and quartz (tholeiites)[22]. If both tholeiites and alkali basalts come from the asthenospheric mantle, the shift from alkali basalt to tholeiitic basalts might be indicative of lithospheric thinning, whereas the reverse trend implies lithospheric thickening[6,9,11].

### 1.2 Silicic magmas

Because most of silicic rocks are derived from the crust, and many factors could induce crustal melting, silicic magmas cannot be used to directly constrain the evolution of the lithospheric mantle. Crustal melting can be caused by within-crust burial heat accumulation, or by the heat accumulated/trapped within the crust by some overlaying heat-insulating strata. The crustal rocks are highly enriched in K, U, Th with excess heat production. In these cases, the crust would melt when the temperature exceeds the minimum solidus temperature of the rocks without the need of mantle heat input. It has been argued that this crustal melting mechanism was important during the pre-Cambrian, because of the high heat production in pre-Cambrian times[23], or crustal thickening due to collisional orogen[24].

The more effective way to induce crustal melting is via heat transfer from mantle to crust. In this case, mantle-derived magmatism commonly takes place earlier than or simultaneously with crustal magmatism. Theoretical modeling shows that conductive heating of the crust by mantle cannot readily induce crustal melting. The most effective way to induce crustal melting is via advective heating through magmatic underplating or intraplating[25]. In the latter case, the involvement of mantle components is the important feature of acidic magmatism in lithospheric extensional region. So far, knowledge regarding magmatic underplating or intraplating is limited. Zhu et al.1) proposed that whether magma underplating or intraplating takes place is dependent upon mantle potential temperature and magma emplacement rate; in the region where a mantle plume exists, magmatic underplating is frequent, and accompanied crustal melting produces A-type and I-type granites but no S-type granites. In extensional region (in the absence of mantle plume), where the magma temperature and magma supply rate are low, intraplating takes place frequently, resulting in the coexistence of S-type and I-type granites. A complexity added to this generalization is that S-type granites can also be produced by crustal thickening.

## 2 Other indicators related to cratonic destruction

The destruction of the North China Craton implies not only change in lithospheric thickness, but also changes in composition of the lithospheric mantle, thermal state and rheological property[4,6]. Accordingly, the start of changes of these processes can be taken as an onset of cratonic destruction. Unfortunately, no geologic expression marches the thermal, rheological and compositional change in depth, making it difficult to assess the indicators of cratonic destruction. Nevertheless, the conceptual evolution from lithospheric thinning to cratonic destruction yields impact on the logics of reasoning, for example, not all cratonic destruction processes is related to lithospheric extension, but more likely resulted from interaction of multiple factors.

## 3 Temporal and spatial distribution of magmatism in North China

The North China Craton remained stable since Proterozoic cratonization. Magmatism did not occur until the Carboniferous-Triassic (Figure 1). Magmatism includes the following stages:

(1) The earliest magmatism occurred in the Mongolian paleo-uplift in the northern margins of the North-China Craton and is characterized by a series of calc-alkaline, I-type granites. The emplacement ages are 324—300 Ma[26–28], probably related to the southward subduction of the Paleo-Asian plate.

(2) Some minor magmas of late Triassic age were emplaced in eastern North China Craton (Figure 1(b)). Examples include the syenites from Jiazishan (Shandong) and alkaline intrusions in Liaodong Peninsula and southern Jilin Province[29–31]. The alkaline rocks from Saima and Bolinchuan likely belong to the east-west belt of alkaline magmatic belt. In the southern part of the province are located some late Triassic I-type diorite-granodiorite, gabbros and syenites.

(3) Jurassic magmatism mainly occurred in the northern margin of the North China Craton, such as Yanshannian belt, eastern Liaoning Province, and Linlong and Kuangyushan (Figure 1(c)). Jurassic magmatism is rare and only sporadically occurred in the interior of the Craton (i.e., the Tongshi igneous complex in western Shandong Province). The Jurassic magmatism is mainly intermediate to silicic. Mafic magmas of contemporaneous ages are very rare with only one reported case for the mafic lamprophyres in Huaziyu in Liaodong Peninsula[5].

(4) The extent and intensity of the Cretaceous magmatism reached the climax (Figure 1(d)). In addition to the occurrence in the Yanshannian belt, Taihangshan area and Sulu-Dabie belt, magmas also occurred in the interior of the North China Craton and in the regions adjacent to the Tanlu Fault. It seems that magmatism migrates with time from the margin to the interior of the craton. Cretaceous magmatism is characterized by the co-existence of mafic and silicic magmas.

(5) Magmas of late Cretaceous and early Tertiary are mostly quartz- and olivine-normative tholeiites, sub-alkali basalts (olivine basalts) and some alkali basalts and mostly distributed in the interior of the extensional basins (Figure 1(e)). Sub-alkali rocks continued to occur but diminished in quantity in the late Tertiary and the Quaternary, while alkali and strongly alkali basalts (basanite and nephelinite) are progressively becoming the dominant rock types and they are mainly distributed in the rift franks.

1) Zhu D, Xu Y G, Luo T Y. The origin of basaltic underplating. Submitted to EPSL.

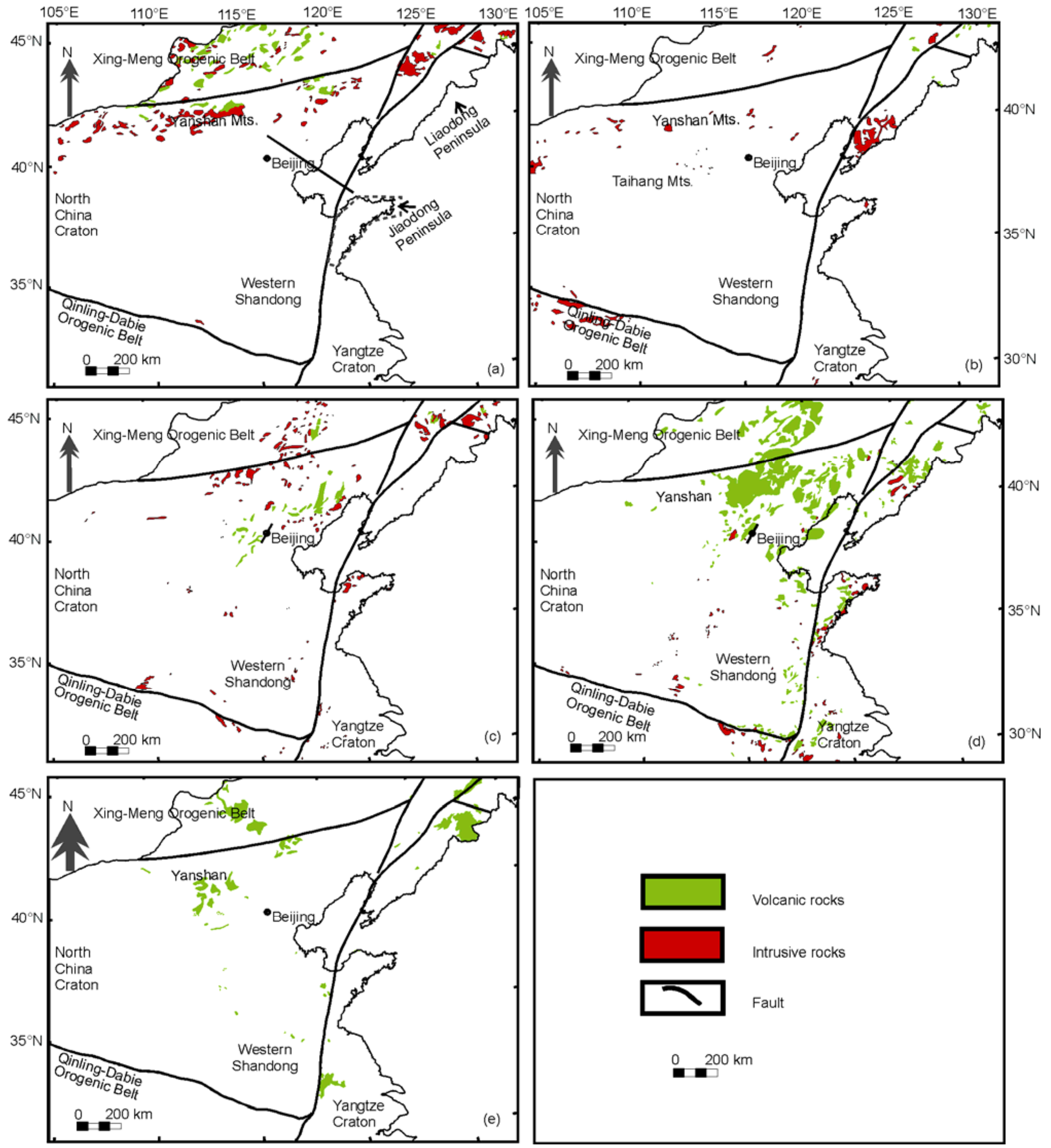


**Figure 1** A map showing distribution of magmas of different ages in the North China Craton. (a) Carboniferous-Permian; (b) Triassic; (c) Jurassic; (d) Cretaceous; (e) Cenozoic.

### 3.1 Temporal evolution in composition of mafic magmas

A wealth of data is now available as to the temporal change in source characteristics of Mesozoic to Cenozoic mafic magmas in North China[6,11,32]. As illustrated in Figure 2, the evolution of the Mesozoic-Cenozoic mafic magmatism in North China can be divided into three stages. The magmas in the first stage ①, characterized by negative $\varepsilon_{\rm Nd}(t)$, were largely derived from the enriched lithospheric mantle[6–8,33–35], whereas those produced during the latest stage ③, characterized by positive $\varepsilon_{\rm Nd}(t)$, were largely derived from the astheno-

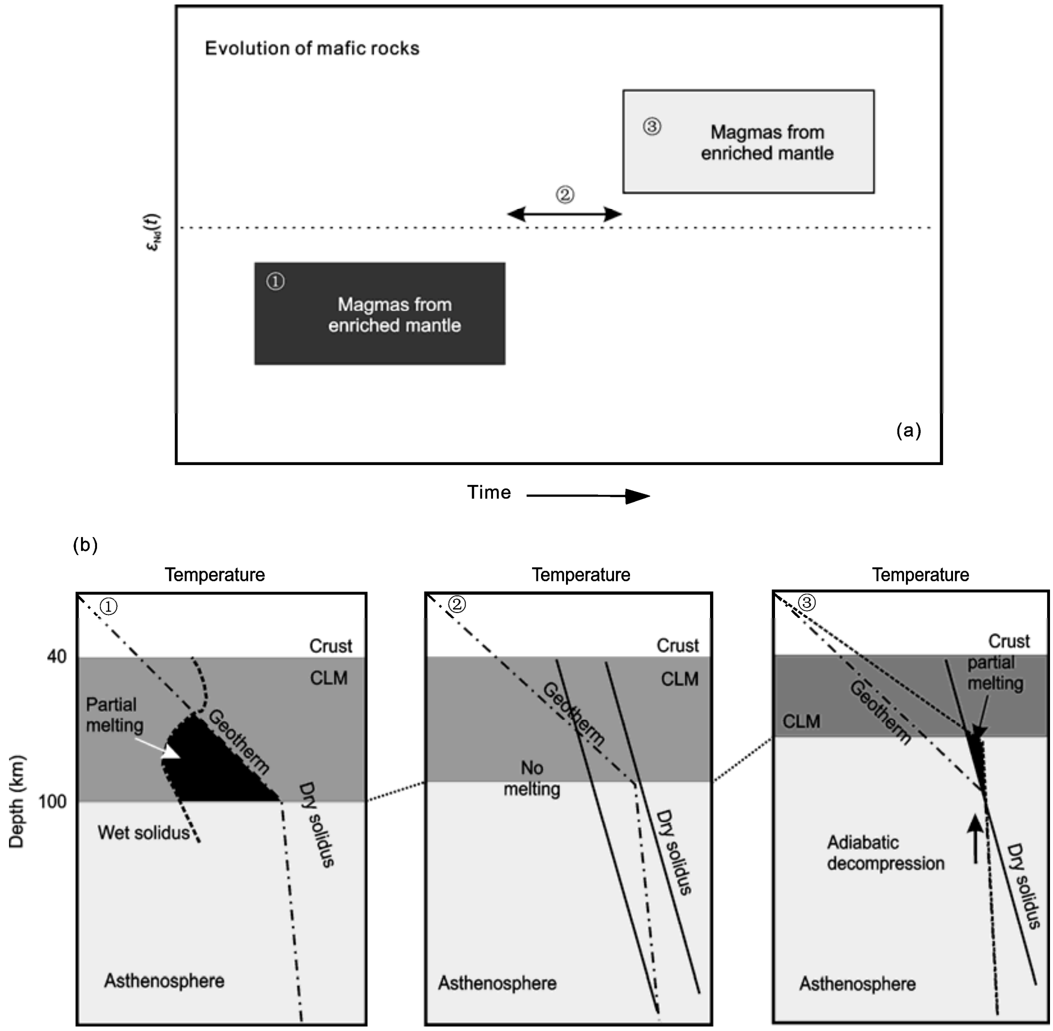


**Figure 2** Diagram illustrating temporal change in source for continental magmatism in extensional setting (a) and relevant interpretation (b).

spheric mantle[6,36–38]. These two stages are separated by a magmatic hiatus (i.e., stage ②).

This evolutionary trend likely reflects the change in melting mechanism during the lithospheric thinning[6,7,11]. In other words, compositional variation in mafic magmas from the eastern NCC is controlled by lithospheric thinning process. The melting of the lithospheric mantle in the first stage was induced by the addition of volatiles that leads to the decrease in melting temperature and by intensified global mantle convection during the early Cretaceous. Nevertheless, the enriched isotopic signature in the early Cretaceous magmas implies a relatively thick lithosphere (> 100 km). Otherwise, magmas with depleted isotopes would be generated.

### 3.2 Temporal evolution in composition of silicic magmas

Jurassic Tongshi igneous complex is the earliest acidic magmatism in the North China Craton. Early syenites (185 Ma) exhibit a geochemical characteristics sharing that of the asthenosphere ($\varepsilon_{Nd}$ = 0.9−4.9)[39], whereas late granites have $\varepsilon_{Nd}$ values of –11.4 and 12.1, $^{87}Sr/^{86}Sr$ between 0.7040−0.7042 and unradiogenic Pb isotopes ($^{206}Pb/^{204}Pb$ = 16.11−16.56; $^{207}Pb/^{204}Pb$ = 15.07−15.17; $^{208}Pb/^{204}Pb$ = 35.87−36.13[7]. Such whole rock isotopic compositions resemble those of the granulite xenoliths included in the Cenozoic basalts from eastern China[40,41]. Consequently, the Tongshi mozogranites likely represent the melting products of the late Archean lower crust[7]. The compositional change exhibited by the Tongshi igneous complex can be understood by heat transfer from mantle to crust.

Jurassic granites are widespread in some weakened zones in Liaodong Peninsula and Jiaodong Peninsula and exhibit adakitic trace element characteristics (Figure 3).

Simultaneous mantle-derived magmas are rare. All these suggest crustal thickening in these regions. Among Cretaceous granites, only few of them show adakitic geochemical feature. Evidence for mantle involvement in genesis of the Cretaceous granites is abundant, suggesting crustal thinning of various extent at that time.

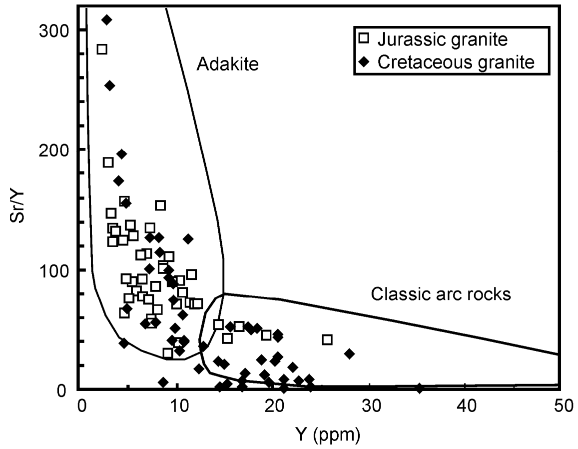


**Figure 3** Sr/Y-Y plot for silicic rocks of different ages in the North China Craton[3,42–50].

## 4 Discussion

### 4.1 The onset of destruction of the North China Craton

The earliest Phanerozoic magmatism in the North China Craton occurred in its northern margin and is characterized by a suite of Carboniferous calc-alkaline, I-type granites. It has been demonstrated that these magmas can be regarded as Andean type continental arc magmatism[27], most likely resulted from southward subduction of the Paleo-Asian oceanic plate underneath the northern margin of the North China Craton. In this sense, the northern margin of the North China Craton has already been re-activated since the late Carboniferous due to the Central Asian Orogency[51].

Another relatively early magmatism in the North China Craton occurred in the late Triassic. Isotopic tracing revealed the involvement of mantle materials in these magmas[29–31,52]. There are different opinions regarding the geodynamics leading to this magmatism. On the basis of the compositional similarity with the post-collisional potassic rocks in typical orogenic zones, Yang et al.[30] suggested that the Triassic magmas were generated in an extensional setting after the collision, therefore marking the end of the collision-orogen. They claimed that all the magmatism later than the Triassic was of intraplate nature. Alternatively, Chen et al.[53] and Xie et al.[52] suggested that the generation of the late Triassic syenite from Jiazishan was related to the slab-breakoff of the Yangtze plate during its subduction underneath the North China Craton; the melting of the upper mantle was induced by the upwelling of the asthenosphere through the slab window. The supporting evidence for this argument includes: (1) limited distribution, mainly in the Sulu-ultrahigh pressure metamorphic belt and its northern extension; (2) the age of the Triassic magmas is about 20 Ma younger than the ultrahigh pressure peak metamorphism, an interval identical to that between slab-breakoff and subduction as predicted by theoretical modeling[54]; and (3) the relatively low Pb isotopic ratio of the late Triassic magmas is inconsistent with the melting of the lithosphere underneath South China as predicted by the post-collisional model. Instead, it is suggestive of the involvement of the lithosphere (including lower crust) under North China.

The occurrence of the late Carboniferous and Late Triassic magmatism in the northern margin of the North China Craton indicated the change in lithospheric structure and thermal structure in that region. It can thus be concluded that it was the multiple episode tectonic amalgamation and associated magmatism around the North China Craton that initiated the destruction of the North China Craton. In this sense, the late Carboniferous can be considered as the onset of the destruction of the North China Craton[27,51]. Of course, the onset of the destruction is diachronous in terms of the space; it is possible that it started from the Late Carboniferous in the northern margin of the North China Craton, whereas it initiated since the Late Triassic in eastern margin of the Craton[31,55]. It is worth noting that these early magmatism was largely confined to the craton's margin, whereas the interior of the craton remained stable at that time, suggesting a limited scale of the lithospheric destruction[4]. Nevertheless, this cannot be taken as an argument against the initiation of the cratonic destruction since the Carboniferous and Triassic. Most likely, the destruction of the North China Craton proceeded heterogeneously in time and space[10].

The tectonic amalgamation around the northern margin of the North China Craton in the Carboniferous-Triassic impacted on the evolution of the North China Craton. A continental arc magmatic belt was generated along the Mongolian Uplift as a result of the southern subduction of the Paleo-Asian Plate. If the subduction was with a low angle, an intra-continental belt of tectonic deformation and magmatism would form behind the continental arc. Actually, this is the site occupied by the Yanshan-eastern Liaoning belt. However, it is difficult to understand because the activation of the Yanshan-eastern Liaoning belt mainly took place in Jurassic, significantly later than the late Carboniferous. More studies are needed to clarify this issue in the future. The influence of the late Triassic North China-South China collision on the evolution of the North China Craton can be traced from the analysis of proto-basins. Except for the continuous sedimentation in the Ordos basin during the middle-late Triassic, a widespread unconformity was developed between the middle and late Triassic in the east part of the North China Craton (Table 1). The reconstruction of the Triassic sedimentation shows that the thickness of residual Paleozoic strata, early-middle Triassic and late Triassic sediments decreases gradually from west to east[56]. In the area that is covered by Triassic strata, the thickness of the Paleozoic strata is stable. In contrast, in the area that lacks Triassic strata, the Paleozoic strata become gradually thinner from west to east. Because North China was a stable basin during the Paleozoic, the thickness of its sediments is expected to be stable. Consequently, the presently observed west-east variation in stratigraphic thickness must reflect the effect of the late erosion. All these suggest that there has been a differential uplift movement in North China by the late Triassic, which resulted in high lands in southeast (erosion) and low lands in northwest (sedimentation). Towards the early stage of the late Triassic, the Ordos Basin experienced a westward retreat around the Taihangshan Gravity lineament (Figure 4).

The late Triassic east-west differentiation of the North China Craton was closely related to the collision between South China and North China. Paleomagnetic studies suggest that the North China-South China collision proceeded first in the east and then in the west. The two plates collided first during the late Triassic in the east of the Xuhuai fault in the Dabie-Sulu region[68,69]. It was then followed by the anti-clockwise rotation of the North China Block of 45°—50° during the middle-late Triassic, and the clockwise rotation of the South China Block of 25°—30°. The final closure of the Tethyan Ocean accomplished to west in the late Triassic[70]. Such a diachronous collision process between North China and Yangtze cratons probably gave rise to the lithospheric thickening in eastern North China Craton and the erosion of the late Triassic and underlying strata. The eclogite xenolith found in the Xuhuai area shows a Sm-Nd isochron age of 219 ± 5 Ma[71], virtually identical to the metamorphism age for the Dabie eclogites (220—240 Ma). If these eclogite xenoliths are metamorphosed phases of the lower crust underneath north China, it provides the petrological evidence for the lithospheric thickening in the eastern North China Craton.

In summary, the characteristics of Triassic magmatism and the distribution of the sedimentary basins in North China strongly suggest that the collision between South China and North China have left significant influence in the evolution of eastern North China Craton[72,73]. This is equally reflected by the modification of the lithospheric mantle by the collision[8,33,74–78].

### 4.2 The end of cratonic destruction

The cratonic destruction or lithospheric thinning is followed by a period of thermal decay. The lowering of thermal gradient leads to the accretion of the lithospheric mantle[4,6,79,80]. During lithospheric accretion, magmas are mainly derived from the asthenospheric mantle and depth of magmatic generation becomes gradually deeper with time. The timing at which lithospheric thinning shifts to lithospheric thickening marks the end of cratonic destruction.

Cenozoic basalts in North China show an increasing alkaline extent with time, suggesting a progressively increasing in origin depth of magmas[6,11]. The present-day surface heat flow (~60 $mW/m^2$) is lower than that in the early Cenozoic (~80 $mW/m^2$)[72,81]. It thus can be concluded that the Cenozoic corresponds to the period of lithospheric accretion. Wu et al.[4] suggested that the destruction of the North China Craton took place before the Cenozoic. The presence of the 100 Ma asthenosphere-derived basalts in Fuxin (western Liaoning province)[37] implies that the destruction of the North China Craton might have taken place prior to 100 Ma[4].

The occurrence of ~100 Ma asthenosphere-derived basalts in Fuxin does suggest that the lithosphere at that time was thinned to some extents. The question is whether the period from 100 Ma to present all corresponds to the period of lithospheric accretion. As discussed above, to define the final timing of cratonic destruction, one needs to know the timing at which the origin depth of magma becomes deeper and the first asthenosphere-derived magmas occur. In other words, only

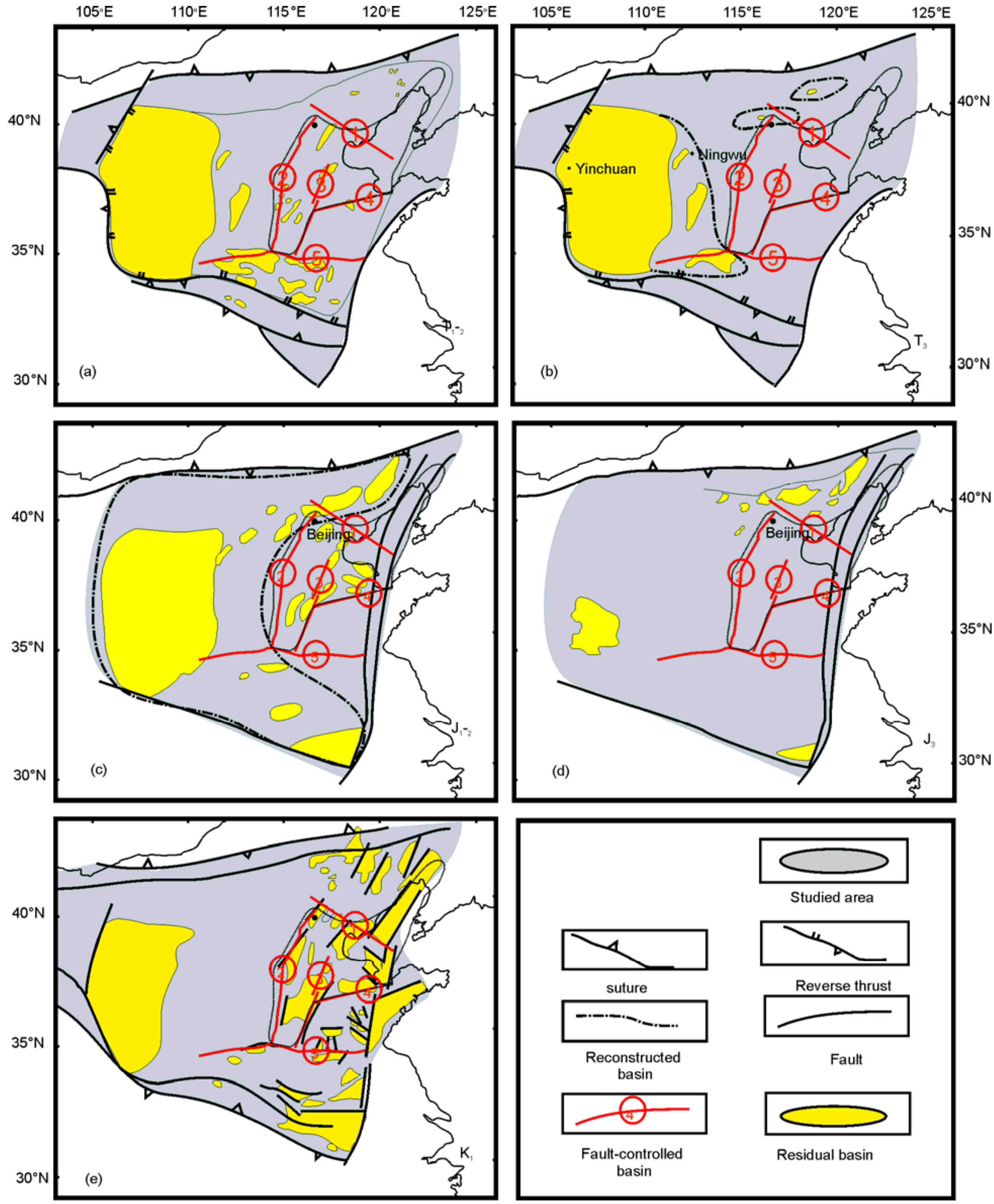


**Figure 4** The evolution of Mesozoic proto-type basins in the North China Craton. (a) Early-Middle Triassic; (b) Late Triassic; (c) Early-Middle Jurassic; (d) Late Jurassic; (e) Early Cretaceous[56–67].

the shift point from lithospheric thinning to lithospheric thickening marks the end of cratonic destruction. So far, two places have been founded recording the transition in magma source from an enriched to depleted mantle; one is Fuxin in western Liaoning, the other is Daxizhuang and Pishikou in Jiaodong Peninsula. The asthenosphere-derived magmas in these two places occurred at ~100 Ma and 73—82 Ma[36,37,82], respectively. It is worth noting that all these magmas are mantle xenolith-bearing strongly alkali basalts and they were followed by some sub-alkali basalts. For instance, the volcanic rocks of Laohutai Formation near Shenyang comprise alkali basalts in bottom and tholeiitic basalts in the upper part. According to the lithospheric lid effect model, it can be inferred that in the early Cenozoic, the lithosphere, at least in some places in North China Craton was still in a thinning period. Given the possible heterogeneous pattern of lithospheric thinning in terms of time and space[11], we suggest that the ending time of the destruction of the North China Craton should vary between the late Cretaceous and early Cenozoic. This argument is consistent with the late Cretaceous tectonic uplift in this area (Table 1).

### 4.3 Duration and climax of destruction of the North China Craton

On the basis of the onset (late Carboniferous-late Triassic) and the end (late Cretaceous-early Cenozoic) of the cratonic destruction, we propose that the destruction of the lithospheric keel beneath the North China Craton was a long process (>100 Ma). This long period was marked by two large-scale magmatism in Jurassic and early Cretaceous[2,3]. Different opinions exist as to the geodynamic setting under which the Jurassic granites were formed. Wu et al.[3] suggested that the Jurassic granites were generated by melting of the crust thickened by the subduction of the Paleo-Asian plate, whereas Li et al.[83] favored an intraplate extensional model. It should be noted that the Jurassic magmas (190—155 Ma)[3] were NNE-distributed, dominated by granites with no mafic rocks. In terms of petro-chemistry, the majority of granites show adakitic characteristics and their isotopic composition indicates a provenance from the old crustal source. Although the absence of contemporaneous mafic magmas in the Liaodong and Jiaodong area could be related to the preservation and exposure, the fact that mafic veins in the Jurassic granites are of Cretaceous ages strongly indicates a minor contribution of the mantle to the generation of Jurassic magmas. According to the adakitic composition of the Jurassic granites, we infer that this episode of magmatism is likely related to crustal thickening[84] as a result of the Pacific subduction[85]. Wu et al.[86] estimated the zircon saturation temperature of the Jurassic granites in the Liaodong Peninsula to be ~750℃, significantly lower than that for the Cretaceous granites. This temperature difference is in support of the idea that the Jurassic granites were formed in a subduction-related tectonic setting. This model predicts a belt of arc magmatism, which is parallel with and lies to the east of the Jurassic granitic belt. More data are needed to confirm this prediction.

The following observations suggest that the lithosphere beneath the North China Craton commenced to thin since the Jurassic. (1) 155 Ma mafic lamproites dyke swans outcropped in Huaziyu, eastern Liaoning province[5]. Their geochemistry is indicative of a derivation from an enriched lithospheric mantle with involvement of some asthenospheric mantle components ($\varepsilon_{\mathrm{Nd}}$ = −10—−1.4). This implies local upwelling of the asthenosphere, probably subsequent to lithospheric thinning. The age of the Huaziyu lamproite dykes corresponds to the terminal timing of the Jurassic granites in Jiaodong and Liaodong. It is thus possible that the local lithospheric extension during the late Jurassic might have resulted from gravity collapse of thickened lithosphere. (2) The Jurassic syenites from Tongshi in the interior of the North China Craton display an OIB-like geochemical characteristic, probably representing melting products of underplated materials of the asthenosphere-derived magmas. The presence of asthenosphere-derived magmas indicates the lithospheric thinning in the interior of the NCC. Such an interpretation is consistent with magmatic evolution trend exhibited by the Tongshi igneous complex.

As discussed above, the early (185 Ma) syenites from Tongsi resulted from melting of asthenosphere-derived magmas[39], whereas the late (177 Ma) mozogranites were derived from an ancient, evolved lower crust[7]. Such a temporal transition in magma characteristics, similar to that displayed by silicic rocks in the Emeishan large igneous province[25], is most likely related to the heat transfer from mantle to crust during the lithospheric thinning. Again this indicates the thinning of the lithosphere beneath the North China since the Early Jurassic. It is also important to note that the Tongshi igneous complex is located along the boundary between EM1 and EM2 mantle domains of the Mesozoic lithosphere in North China[8]. If the EM1-type mantle domain represents the proto-lithospheric mantle beneath North China, and the EM2-type mantle domain represents the lithospheric mantle unmodified by subduction of the Yangtze plate, we tentatively propose that the formation of the Tongshi igneous complex was probably related to local break-off of the subducting Yangtze plate underneath

North China.

Compared to the Jurassic magmatism, the extent and intensity of the Cretaceous magmatism is more important (Figure 1(c)). The Cretaceous magmatism is characterized by a diffusive distribution, co-occurrence of silicic and mafic magmas, an increasing extent of mantle involvement and a petrochemistry transitional between I- and A-type granites[30]. The Jurassic magmas not only occurred in the margins of the Craton, but also in the interior of the craton. In addition, the early Cretaceous large-scale magmatism was timely coeval with the formation of metamorphic complex[87], extensional basins[88] and gold deposits[89] in North China. All these demonstrate that North China entered a period of lithospheric extension in the Early Cretaceous.

As a whole, the two episodes of magmatism in North China were produced under different tectonic settings. Tectonic analysis suggests that the Jurassic corresponds to a compressional setting, whereas the Cretaceous marks an extensional setting[85,90,91]. The change-over of tectonic setting took place at ~145 Ma, probably related to change in direction of the pacific subduction from NW to NEE[92]. During the middle Jurassic, the Izanagi Plate subducted westward underneath the eastern Asian continent at a velocity of 4.7 cm/a[93,94]. At that time, eastern North China was under a compressional setting, influenced by multiple forces generated by converging the Yangtze plate, Izanagi plate and Mongolian plate. In the Late Jurassic, the Siberian plate collided with the North China-Mongolian plate[95], meanwhile the North China Block uplifted. At the earliest stage of early Cretaceous, a sudden change in the direction and velocity of the Izanagi plate took place, leading to its northward subduction with a velocity of 30 cm/a underneath the eastern Asian continent[93]. The early Cretaceous marked a critical period of tectonic change-over in eastern North China Craton. This period is characterized by the formation of the widespread depressional basins, and of volcanic rocks in Yanshan, western Liaoning and Yinshan belts. The rapid, northward subduction of the Izanagi plate induced the sinistral slip movement of the Tanlu fault[94,96]. There is a good coupling between the late Jurassic crustal uplift, early Cretaceous tectonic change, the collision between the North China Block and Siberian-Mongolian plate, and sudden change in direction and velocity of the Izanagi plate. It appears that the destruction of the North China Craton was controlled by a combination of forces issued from all adjacent blocks, rather than by a single interaction between two blocks.

The long time scale for the destruction of the North China Craton is not in contradiction with the climax of the cratonic destruction. Like many other geologic processes, cratonic destruction also has its initiation, climax and end. It is important to stress that, although the early Cretaceous was the peaked period of the cratonic destruction, lithospheric thinning is not restricted to this period, because lithospheric thinning is not necessarily accompanied by magmatism, in particular in the case of thick cratonic keel. Enriched components commonly resided at depths of ~100 km in the continental lithospheric mantle[97]. If the initial thickness of the lithosphere under North China was ~200 km[6,98,99], despite their relatively lower melting temperature, these enriched components would not melt because of the limited heat transfer from the asthenosphere due to the long distance of ~100 km between the metasome and underlying asthenosphere. This allows the formation of the characteristic isotope composition of enriched components (low Nd and high Sr isotopic ratios). Only when the lithosphere is thin enough, the enhanced heat transfer from the asthenosphere to the lithosphere allows the cross between the geotherm and solidus of enriched mantle. On the basis of this analysis, we believed that the lithosphere has already been thinned prior to the 120－130 Ma peak magmatism, with some sporadic Jurassic magmatism[5,8,39] as expression. If the lithospheric thinning took place uniquely in the Early Cretaceous, it is difficult to understand the considerable contrast in isotopic composition between the early Cretaceous enriched lithospheric mantle and peridotite xenoliths entrained in Cenozoic basalts in this region.

Figure 5 depicts the main stages of the evolution of the lithospheric mantle beneath north China, as discussed above.

### 4.4 Roles of weakened lithospheric zones in heterogeneous destruction of the North China Craton

Both surface geology and magmatic records suggest a heterogeneous lithospheric thinning pattern in North China in terms of time and space. It is clear from Figure 1 that the early magmatism is mostly restricted to the peripheries of the craton, magmas occurred in the interior of the craton until the Jurassic and Cretaceous. On the basis of the above discussion, if magmatism marks the cratonic destruction, it implies that the destruction of the craton was initiated from weakened lithospheric

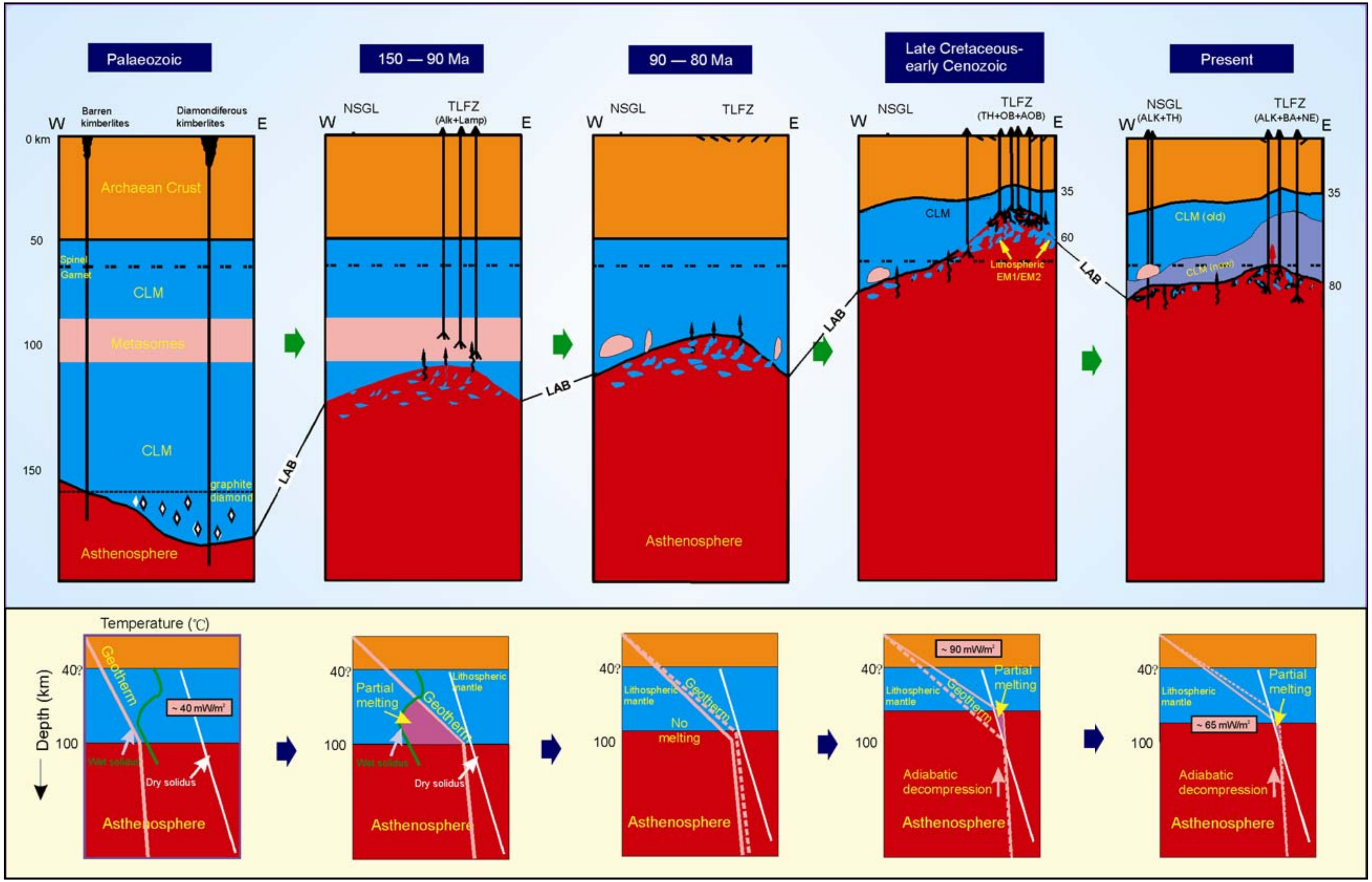


**Figure 5** A multiple episodic model for the evolution of the lithosphere underneath the North China craton and the relationship between thermal state of the lithosphere and mantle solidus at different stages (modified after ref. [6]). TLFZ, Tan-Lu Fault; NSGL, North-South Gravity Lineament.

zones, starting from cratonic margins and then expanding towards the interiors. Such a margin-to-inside destruction pattern highlights the roles of plate boundary and/or intraplate weakened zones in cratonic destruction. In fact, the eastern North China Craton is surrounded by Phanerozoic orogens. To the north lies the Xing-Meng Orogen formed as a result of the closure of the Paleo-Asian Ocean; to the south is the Qinling-Dabie orogen; to the east is the Sulu metamorphic belt and Pacific subduction, and to the west is the Proterozoic Trans-North China orogen. All these belts are weakened lithospheric zones and thus became the focus of initiation of lithospheric thinning. Once the topographic contrast of base of lithosphere is created, local mantle convection can be significantly intensified[100] and the lithospheric thinning expanded towards the cratonic interior. This pattern of the Mesozoic destruction of the North China Craton is also registered in modern geology. The Ordos Block is regarded as residues left by the removal of the thick lithospheric keel beneath the eastern North China Craton. The Ordos is bounded by two Cenozoic rifts[101]; Yingchuan-Hetao rift to northwest and the Shanxi-Shaanxi rift to east. Recent seismic tomography1) shows that the lithosphere beneath these two rifts is of 80－100 km, significantly thinner than that under the Ordos Block (200 km). This is suggestive of the lithospheric thinning currently taking place at the margins of the Ordos Block, a process similar to that of Mesozoic lithospheric thinning in the eastern NCC.

This observation is corroborated with the contrasting evolutionary trends exhibited by Cenozoic basalts from both sides of the Daxin'anling-Taihang gravity lineament. In the western North China Craton, magmas evolved from xenolith-bearing alkali basalts of late Eocene-Oligocene age to coexisting alkali and tholeiitic basalts of late Miocene-Quaternary age. This temporal variation in basalt geochemistry is interpreted as reflecting progressive lithospheric thinning in the western NCC during the Cenozoic[9], because alkali basalts are generated at greater depth than tholeiitic basalts[22,103] and if the lithospheric lid effect is valid. An opposite trend is observed for Cenozoic basalts from the eastern NCC, with early Tertiary magmas being mostly tholeiitic and weak alkali affinity, whereas late Tertiary and Quaternary basalts being alkali and strongly alkaline. This suggests lithospheric thickening in the eastern NCC, probably related to regional thermal decay following peak magmatism in the late Cretaceous-Early Tertiary[6,72]. Such contrasting lithospheric processes may reflect diachronous extension in the North China Craton, with initial extension in the eastern North China Craton owing to the late Mesozoic Paleo-Pacific subduction and subsequent extension in the western North China Craton induced by the early Tertiary Indian-Eurasian collision[100].

In addition to the weakened lithospheric zones around the cratonic peripheries, those in the interior of the North China Craton (e.g., Tanlu fault, Trans-North China orogen) also played a key role in the destruction of the North China Craton[95,103–105]. In the early Cretaceous, northward subduction of the Izanagi plate induced sinistral slip of the Tanlu fault, which also became an important channel of upwelling of the asthenosphere. This makes the regions adjacent to the Tanlu fault the thinnest regions in North China, where the lithospheric mantle is mostly newly accreted. In contrast, the areas remote from the Tanlu Fault (e.g., Hebi) is underlain by the co-existing new and old lithospheric mantle[103,106].

## 5 Conclusions

The time scale of magmatism can be used to constrain the processes of lithospheric thinning, but is not necessarily equal to the duration of lithospheric thinning. It is suggested that the thinning of the lithosphere beneath the North China Craton might have initiated from the edge of the craton, in response to the late Carboniferous southward subduction of Paleo-Asian plate and late Triassic collision between North China and South China. The lithospheric thinning attained its climax during the late Jurassic-early Cretaceous, and continued till the end of late Cretaceous-early Cenozoic. The duration of the destruction of the North China Craton is over 100 Ma, suggesting a relatively slow, rather than a dramatic thinning process.

The weakened lithospheric zones along the cratonic margins and interiors played an important role in cratonic destruction, partly accounting for the heterogeneous destruction pattern. Magmatism in North China initiated since the late Carboniferous-late Triassic and was

1) Chen L, Cheng C. Seismic evidence for significant lateral variations in lithospheric thickness beneath the central and western North China Craton. Submitted to Geology, 2008

mainly confined to cratonic margins, in contrast, magmatism in Early Cretaceous also occurred in the interior of the craton. It is thus suggested that the destruction of the North China Craton likely migrated from periphery to interior. The regions adjacent to the Tanlu fault are the most significantly thinned area.

On the basis of temporal and spatial distribution of magmatism, we suggest that tectonic factors that controlled destruction of the North China craton may be multiple. The late Carboniferous southward subduction of Paleo-Asian plate and late Triassic collision between North China and South China may have re-activated the craton by influencing the thermal and integral structure of the craton. The former was probably responsible for the formation of Yan-Liao tectonic belt, the latter not only led to the east-west differentiation of the North China, but also resulted in significant modification of lithospheric structure and composition. The Pacific subduction underneath the eastern Asian continent played a determinant role in the cratonic destruction, governing the distribution patterns of post-Mesozoic basins and major tectonic configuration, temporal change of magmatism and formation of the North-South gravity lineament.

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